EXHIBIT 12

A comparative study of the AV1 and HEVC video codecs

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Abstract

Video compression technologies have been evolving for several years with the aim of providing high-quality video with minimum bandwidth consumption. The rise of streaming services and the need for high-quality video has led to the development of video codecs such as AV1 and HEVC. In this research paper, we compare the two codecs by examining their performance, encoding complexity, licensing, and adoption rate. Our findings suggest that while AV1 offers slightly better compression efficiency, it has a much higher computational complexity than HEVC. We will provide a short description of the salient features of each codec followed by performance analysis with the help of reference studies.

1. Introduction

Video compression is an essential component of multimedia applications as it enables efficient transmission and storage of video data. The consumption of multimedia content has not stopped growing and represents the largest segment of internet traffic. The increasing consumption of more immersive video formats and higher resolution has pressured the industry and scientific community into innovating efficient video compression techniques. Video compression techniques aim to reduce the amount of data required to represent a video signal while maintaining its visual quality. This is achieved by exploiting the temporal and spatial redundancy in the video signal. Video codecs play a critical role in the delivery of high-quality video content. HEVC (High-Efficiency Video Coding) and AV1 (AOMedia Video 1) are two of the prominent codecs that have gained attention in the industry.

HEVC, also known as H.265, was developed by the Joint Collaborative Team on Video Coding (JCT-VC) and was first released in 2013. HEVC is protected by several patents and requires royalty payments. High Efficiency Video Coding (HEVC) is the currently popular state-of-the-art video compression standard. It provides significant improvements in compression efficiency compared to its predecessor, H.264, needing only half the bandwidth consumption for the same visual video quality. HEVC achieves this by introducing optimized features such as flexible block partitioning, intra-coding, inter-coding and loop filtering techniques. The first version of HEVC was released in 2013 and a new collaboration between ITU-T and ISO/IEC was established in 2015. The Joint Video Experts Team on future video coding (JVET) was created to define a new standard Versatile Video coding (VVC). Currently, JVET maintains VTM (Versatile Video Coding Test Model) for VVC based on the HEVC core. VVC is currently in the developmental stages and will not be the primary focus of this paper.

AV1, on the other hand, is a relatively new video compression technology developed by the Alliance for Open Media (AOMedia) and released in 2018. Google's WebM project first released a codec entitled VP8, which was later succeeded by VP9. In 2015, several high-tech companies, such as Google, Apple, Netflix, Mozilla, Cisco, IBM, NVIDIA, Amazon, and ARM, joined and founded the Alliance for Open Media

(AOMedia), which is responsible for the creation of a new royalty-free codec, named AOMedia Video 1 (AV1). The AV1 encoder used the proprietary VP9 video coding scheme as a starting point, but many other enhancements have been included in the project over the last few years to increase compression efficiency. AV1 is targeted for internet and web applications as well as OTT providers like movie platforms. It is designed to provide better compression efficiency than HEVC and is royalty-free, which makes it an attractive alternative for many applications.

2. Key Salient Features of the HEVC and AV1 codecs

We compare some key salient features of both codecs including some technical details about their implementation.

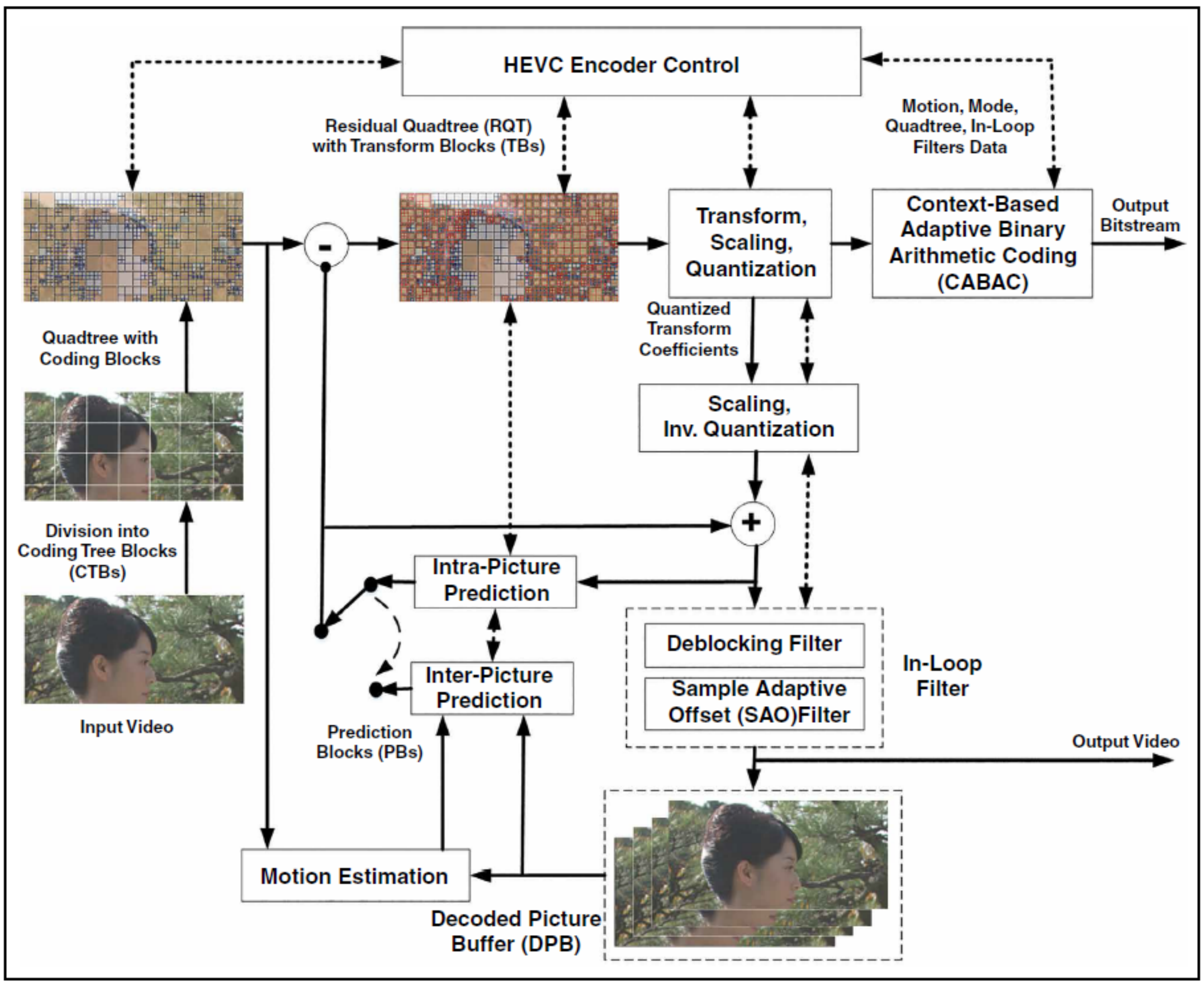

Figure 1. Schematic block diagram of the H.265/MPEG-HEVC encoder [11]

2.1 HEVC Technical Details

HEVC is a block-based video coding standard that uses intra-frame and inter-frame prediction along with transform coding to achieve high compression efficiency. It uses 8x8 to 64x64 block sizes to divide each

frame into smaller units, and each block is further divided into sub-blocks. HEVC uses four main types of prediction: intra, inter, motion vector, and residual. Intra-prediction is used to predict the pixel values within a block from the neighboring pixels within the same frame. Inter-prediction is used to predict the pixel values from the previous and future frames. Motion vector prediction is used to predict the motion of objects in the frame, while residual prediction is used to predict the difference between the original pixel values and the predicted values.

HEVC uses a transform coding technique called High-Efficiency Transform (HEVC) to compress the prediction residuals. HEVC uses two types of transforms: discrete cosine transform (DCT) and discrete wavelet transform (DWT). The DCT is used for smaller block sizes, while the DWT is used for larger block sizes. Figure 1 shows the schematic block diagram of the HEVC video codec.

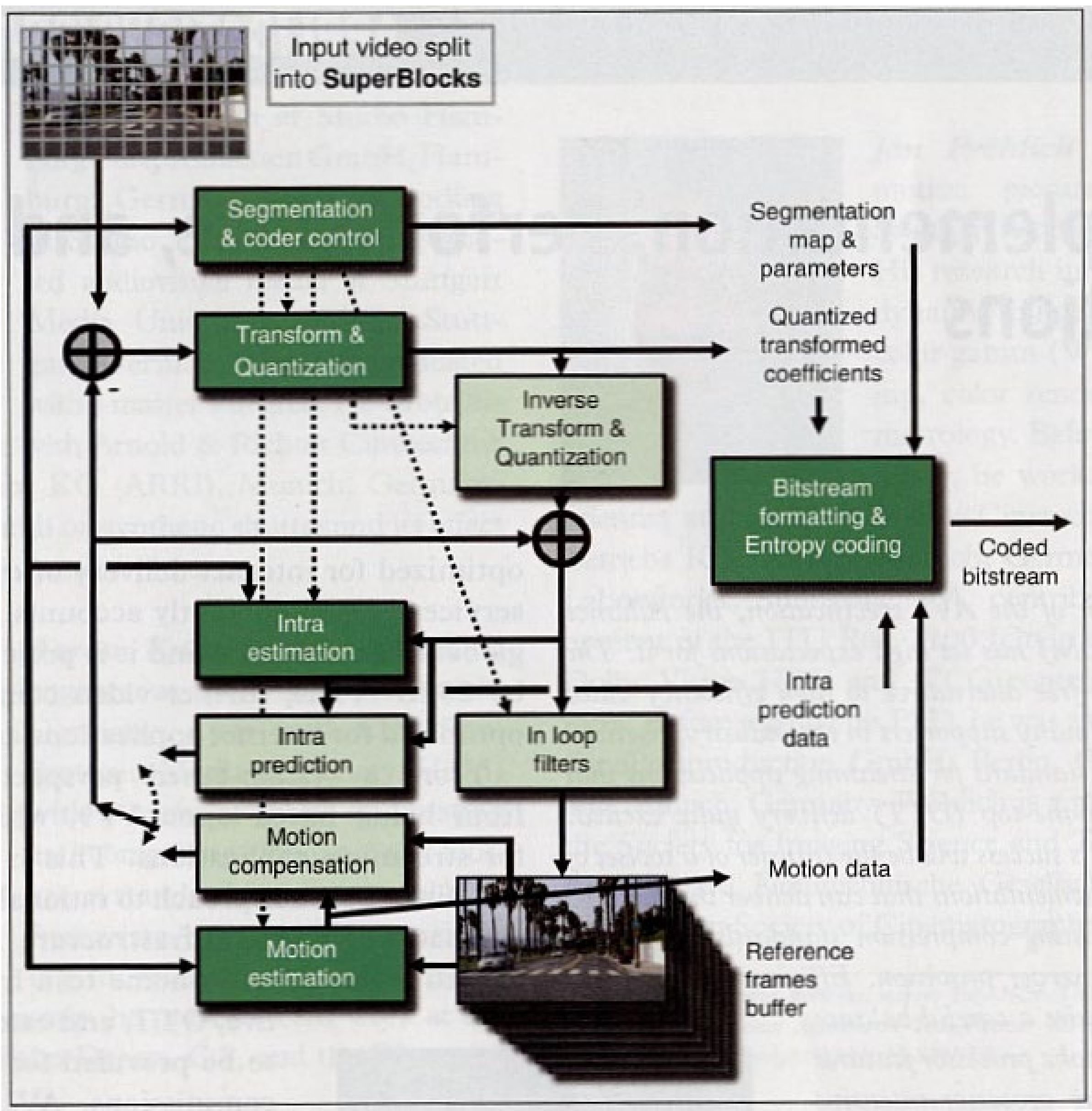

Figure 2. Schematic block diagram of the AV1 encoder [13]

2.2 AV1 Technical Details

AV1 is an open-source video codec that uses the same block-based approach as HEVC to achieve high compression efficiency. However, it employs more advanced techniques such as dynamic motion vector referencing and Daala-based entropy coding. AV1 also uses a prediction technique called bi-directional prediction, which is not present in HEVC. There are different versions available, AV1-libaom, which is reference av1 software, rav1e encoder backed by Vimeo and Mozilla, SVT-AV1 backed by Intel and Netflix and dav1d decoder offering further optimizations related to processing. AV1 has many enhancements: superblocks are introduced (up to 128x128 pixels) with recursive portioning compared to VP9, leading to better quality; Eight intra-prediction directional modes are provided for motion vector predictions; rectangular DCT (Discrete Cosine Transform) and asymmetric DST (Discrete Sine Transform) are available; three profiles (Main, High, Professional) are available with higher than 8 bits depth.

AV1 uses a similar block-based approach as HEVC, but with smaller block sizes. AV1 uses block sizes ranging from 4x4 to 64x64, and each block is further divided into sub-blocks. AV1 uses intra-frame prediction, inter-frame prediction, and bi-directional prediction to achieve high compression efficiency. Intra-frame prediction is used to predict the pixel values within a block from the neighboring pixels within the same frame, while inter-frame prediction is used to predict the pixel values from the previous and future frames. Bi-directional prediction is used to predict the pixel values using both past and future frames. AV1 also employs a transform coding technique called Multi-symbol Arithmetic Coding (ANS). ANS is a variant of arithmetic coding that is more efficient than the Huffman coding used in HEVC. ANS uses a probabilistic model to encode symbols, which reduces the number of bits required to represent the symbols. Figure 2 shows the schematic block diagram of the HEVC video codec.

2.3 Licensing

Licensing is a critical factor in the comparison of AV1 and HEVC. HEVC is patented, and licensing fees are required for its use. This has hindered its adoption rate and made it less attractive to smaller companies and organizations. On the other hand, AV1 is an open-source codec that is free to use. This makes it a more attractive option for companies and organizations looking for a cost-effective solution.

2.4 Adoption Rate

HEVC is currently the dominant codec in the market, with widespread adoption in devices such as smartphones, TVs, and streaming services. However, AV1 is rapidly gaining popularity due to its better compression efficiency and open-source licensing. Several streaming services, such as Netflix and YouTube, have already adopted AV1 for video delivery. In addition, major browser vendors, including Google and Mozilla, have also announced support for AV1 in their browsers.

2.5 Playback Performance Comparison

HEVC and AV1 require compatible hardware and software to decode and play back videos efficiently. HEVC and AV1 both require higher processing power than older codecs, such as H.264. In terms of playback performance, both codecs have similar requirements. However, some studies have shown that HEVC may perform slightly better than AV1 in terms of decoding speed and playback efficiency. This is because HEVC has been available for a longer time and has been optimized for various hardware and software platforms.

3. Performance Comparison of HEVC and AV1 codecs

For any codec, the important points for comparison are the efficiency, quality, and complexity. The first two are correlated since the quality is dependent on compression rate chosen, also known as the bitrate, especially for streaming applications.

3.1 Compression Efficiency and Quality

Compression efficiency refers to the ability of a compression technology to reduce the size of the video data while maintaining its visual quality. Several studies have been conducted to compare the compression efficiency of HEVC and AV1, showing significant gains for AV1 over the years.

In 2018, Akyazi et al [1] performed subjective quality evaluation tests to benchmark the compression efficiency of AV1, HEVC/H.265 and VP9 codecs assuming a broadcasting scenario. The compression efficiency of AV1 was slightly below HEVC/H.265 on average over all contents tested, with 1.9%and 3.2% more bitrate requirements based on objective and subjective metrics, respectively. At very high bitrates, there is no sufficient statistical evidence showing differences in performance for any of the codecs.In 2019, Katsenou et al [2] also concluded that the difference in the perceived quality between HEVC and AV1 is not significant for adaptive video streaming applications. In 2019, Bender et al [3], compared the compression efficiency and the computational cost of AV1 and HEVC standard using equivalent quantization parameters in both encoders to measure the Bjontegaard Delta (BD)-rate accurately. Their results showed that the AV1 reference software requires an average computational cost 14.64 times greater than the HEVC Model, with a BD-rate increase of 16.35% in comparison to HEVC.

In 2019, Panayides et al [4], first compared the performance of VVC, AV1 and HEVC for medical applications. Experimental evaluation based on three datasets (ultrasound, emergency scenery, and general-purpose videos) demonstrate that VVC outperforms all rival codecs while AV1 achieves better compression efficiency (6-9%) than HEVC in all cases but low-resolution (560 x 448@40Hz) ultrasound videos of the common carotid artery. In 2020 Gavrovska et al [5], compared the performance of SVT-AV1 (a variant of AV1) with VP9 and HEVC. The results showed that computational cost was 25 times higher for AV1 but the peak signal-to-noise-ratio (PSNR) was best for AV1 followed by VP9 (5% lower) and HEVC (15% lower).

In 2020, Mansri et al [6], compared the performance of several codecs for low-delay video applications. Their results showed that AV1 outperforms HEVC by an average of 6.55% in bit-rate savings using PSNR as the metric, with the gain much higher for low motion and moderate texture videos. On the other hand, AV1 computational complexity was extremely high (more than 50 times higher) and not suitable for applications with low end-to-end delay requirements such as video surveillance systems.

In 2020, Ashimov et al [7], compared H.264, H.265 and AV1, for the case of gaming videos, assuming a full HD streaming scenario. The performance of the codecs was assessed in terms of objective video quality metrics (PSNR, SSIM and VMAF) and subjective video quality assessment. AV1 achieved a better level of video quality both in terms of objective and subjective VQA, for almost all bitrates and content considered. The improvement was remarkable in particular for the lower range of bitrates considered.

In 2021, Pourazad et al [8], evaluated the performance of HEVC, AV1, and VVC in terms of PSNR, SSIM, and HDR-VDP, for 16:9 HDR video sequences captured in 4K and 8K resolutions. Results indicated that the performance of the AV1 and HEVC codecs is highly related to the content complexity and resolution.

Specifically, HEVC seems to be slightly more efficient for content with motion, while AV1 performs better for 8K content with low complexity. Both codecs performed similarly for the subjective quality measures.

In 2021, Nguyen et al [9], presented a compression efficiency evaluation for the AV1, VVC, and HEVC video coding schemes in a typical video compression application requiring random access. The latter is an important property, without which essential functionalities in digital video broadcasting or streaming cannot be provided. For the evaluation, they employed a controlled experimental environment that basically follows the guidelines specified in the Common Test Conditions of the Joint Video Experts Team and their freely available reference software implementations. Depending on the application-specific frequency of random-access points, the experimental results show averaged bit-rate savings of about 10–15% for AV1 and 36–37% for the VVC reference encoder implementation (VTM), both relative to the HEVC reference encoder implementation (HM) and by using a test set of video sequences with different characteristics regarding content and resolution. A direct comparison between VTM and AV1 reveals averaged bit-rate savings of about 25–29% for VTM, while the averaged encoding and decoding run times of VTM relative to those of AV1 are around 300% and 270%, respectively. For UHD content the bit-rate savings were found to be larger for both AV1 and VTM. Specifically, UHD-related bit-rate savings were measured as 14% for AV1 and 42% for VTM, both relative to HM, and 32% when comparing VTM to AV1. The AV1 and VVC reference encoders required averaged encoding run times relative to that of the HMencoder by a factor of more than three for AV1 and more than nine for VTM. On the other hand, the decoding run times indicated that the decoder complexity is manageable for both AV1 and VTM with an averaged decoding run time relative to that of the HM decoder of about 66% for AV1 and 182% for VTM, respectively.

In 2022 Katsenou et al [10], performed a comprehensive comparison of HEVC and AV1 encoders using an extensive video dataset, referred to as BVI-CC, which comprises a complete set of 306 encodings using VVC, HEVC, and AV1, on nine representative source sequences typically used by the standardization bodies. The source sequences native spatial resolution was Ultra High Definition (UHD), 3840x2160. Additionally, the sequences were spatially downscaled to 19201080, 1280720, and 960544 resolution and three experiments were designed. Two experiments were traditionally configured using constant resolution, one at UHD and one at HD. The third experiment was designed on an adaptive bit rate use case implementing the Dynamic Optimizer (DO) approach. Data collected during the quality assessment included: (i) anonymized opinion scores from psychovisual experiments in labs and (ii) values of six commonly used objective quality metrics.

Table 1 summarizes the Bjøntegaard Delta measurements (BD-rate) of AOM AV1 (for three resolution groups) and VVC VTM (for Resolution Group A and B only) compared with HEVC HM, based on both PSNR and VMAF. For the tested codec versions and configurations, it can be observed that AV1 achieves an average bit rate saving of 7.3% against HEVC HM for the UHD test content assessed by PSNR, and this figure reduces (3.8%) at HD resolution. When VMAF is employed for quality assessment, the coding gains of AV1 over HM are slightly higher, averaging 8.6% and 5.0% for UHD and HD respectively. Comparing to AV1, VTM provides significant bit rate savings for both HD and UHD test content, with average BD-rate values between -27% and -30% for PSNR and VMAF. For resolution group C, where VMAF-based DO was applied for HM and AV1, the coding gain achieved by AV1 is 6.3% (over HM) assessed by VMAF, while there is a BD-rate (1.8%) loss when PSNR is employed. In overall conclusion,

the performance of AV1 makes a small improvement over HM on the test content, and both AV1 and HM perform (significantly) worse than VTM.

Table 1. Codec comparison results based on PSNR and VMAF objective quality metrics. Here Bjøntegaard Delta Bjøntegaard (2001) measurements (BD-rate) were employed, and HEVC HM was used as benchmark [10].

Resolution Group	A (UHD)				B (HD)				C (HD-DO)	
Codec	PSNR		VMAF		PSNR		VMAF		PSNR	VMAF
Sequence\BD-rate	AV1	VTM	AV1	VTM	AV1	VTM	AV1	VTM	AV1	AV1
AirAcrobatic	-12.1%	-25.5%	-12.0%	-28.6%	-2.6%	-21.7%	4.2%	-20.0%	13.3%	-0.1%
CatRobot	-6.2%	-38.0%	-12.8%	-39.6%	-4.0%	-37.7%	-10.4%	-41.2%	-2.1%	-11.3%
Myanmar	4.3%	-17.2%	1.3%	-21.3%	6.5%	-15.5%	3.5%	-18.6%	8.4%	5.1%
CalmingWater	-15.5%	-21.5%	-9.6%	-18.9%	-15.7%	-22.6%	-10.2%	-19.6%	-13.0%	-10.4%
ToddlerFountain	-6.6%	-18.7%	-2.0%	-17.4%	-8.1%	-18.2%	-3.7%	-16.4%	-7.8%	-7.3%
LampLeaves	-6.8%	-26.2%	-6.2%	-26.1%	-2.8%	-23.7%	-0.4%	-24.8%	6.7%	-1.2%
DaylightRoad	-3.8%	-38.0%	-12.4%	-40.3%	-0.9%	-37.6%	-10.4%	-42.4%	0.9%	-9.8%
RedRock	-3.5%	-32.5%	-9.0%	-37.9%	0.8%	-31.5%	-6.4%	-37.7%	16.1%	-8.0%
RollerCoaster	-15.3%	-39.9%	-14.5%	-41.7%	-7.9%	-38.9%	-11.5%	-39.8%	-6.6%	-13.5%
Average	-7.3%	-28.5%	-8.6%	-30.2%	-3.8%	-27.5%	-5.0%	-28.9%	1.8%	-6.3%

Table 2. Aggregated significant difference of perceived quality among the tested codecs based on the ANOVA. The first ratio represents the number of sequences where statistically significant difference has been recorded. The ratio in the parentheses show which codec is significantly better (+) or worse (-) in the pairwise comparison of horizontal/vertical codec [10].

	Resolution Group A			Resolution Group B			Resolution Group C	
Codecs	AV1	HM	VTM	AV1	HM	VTM	AV1	HM
AV1	-	4/36, (2/-2)	9/36, (0/-9)	-	3/36, (0/-3)	17/36, (0/-17)	-	5/45, (0/5)
HM	4/36, (2/-2)	-	10/36, (0/-10)	3/36, (3/0)	-	15/36, (0/-15)	5/45, (-5/0)	-
VTM	9/36, (9/0)	10/36, (10/0)	-	17/36, (17/0)	15/36, (15/0)	-	-	-

Table 2 shows subjective quality assessment of the codecs and in most cases AV1 and HM result in equivalent video quality according to the viewers and VTM in many cases prevails both codecs.

In 2021 Grois et al [11], compared the performance of emerging codecs EVC and VVC, in terms of both coding gains and computational complexity, to their predecessor— the HEVC video coding standard. In addition, AV1 was used as an alternative baseline and provide corresponding comparison results. Figure 3 shows the results of the study for compression efficiency. AV1 provides bitrate savings of about 20% compared to the HEVC constant bitrate (CBR) encoding (i.e., with the rate control switched off) as a tradeoff of the computational complexity increase by a factor of ~3.4, on average.

TABLE 7. Summary of experimental results of bitrate savings in terms of BD-BR $PSNR_{YUV}$ of VVC, EVC, and AV1 encoders versus HEVC encoder per JVET VVC CTC.[13,27] AV1 encoder is evaluated with the two-pass rate control (i.e., in a two-pass VBR mode), while the rate control in VVC, EVC, and HEVC encoders is disabled.

Classes of sequences	HM 16.18 is an anchor		
	VVC vs. HEVC	EVC vs. HEVC	AV1 (in a VBR mode) vs. HEVC
Class A1	−39.57%	−27.26% (excl. "Campfire")	−19.46%
Factor of the HM encoder run Time	8.26×	2.91×	3.09×
Class A2	−42.86%	−30.51%	−20.50%
Factor of the HM encoder run time	9.33×	4.51×	3.60×
Class B	−37.18%	−23.28%	−24.35%
Factor of the HM encoder run time	10.00×	5.20×	4.25×
Class C	−30.32%	−17.49%	−15.64%
Factor of the HM encoder run time	11.75×	6.29×	3.20×
Class D	−27.46%	−15.83%	−9.59%
Factor of the HM encoder run time	13.00×	6.67×	3.80×
Class F	−42.41%		−16.34%
Factor of the HM encoder run time	6.66×		1.98×
Average BD-BR	−36.11%	−21.98%	−17.52%
Factor of the HM encoder run time	10.49×	5.25×	3.58×

TABLE 8. Summary of experimental results of bitrate savings in terms of BD-BR $PSNR_{YUV}$ of VVC, EVC, and AV1 encoders versus HEVC encoder per MPEG-EVC CTC.[29] AV1 encoder is evaluated with the two-pass rate control (i.e., in a two-pass VBR mode), while the rate control in VVC, EVC, and HEVC encoders is disabled.

Classes of sequences	HM 16.18 is an anchor		
	VVC vs. HEVC	EVC vs. HEVC	AV1 (in a VBR mode) vs. HEVC
Class A	−41.54%	−29.21%	−19.98%
Factor of the HM encoder run time	8.02×	4.35×	2.69×
Class B	−37.18%	−23.28%	−24.35%
Factor of the HM encoder run time	10.00×	5.36×	4.25×
Average BD-BR	−39.36%	−26.24%	−22.40%
Overall factor of the HM encoder run time	8.96×	4.83×	3.40×

Figure 3. Experimental Results for compression efficiency for different encoders [11].

It can be observed that the observed compression efficiency for AV1 has improved over time and current studies show that it can achieve a bitrate saving of 7% to 20% depending upon the content and image size. It may be observed that VTM (VVC codec platform) is very competitive and beats both Av1 and HEVC by significant margins of up to 27%. Also, based on comprehensive objective and subjective tests, the difference in perceived quality is not significant between the two codecs.

3.2 Computational Complexity

Many of the compression efficiency studies also measured the computational complexity of the codecs. The variation in the results was very wide and depended upon the content, with reported results

ranging from 3 times to 50 times higher encoding complexity for AV1. The tests also indicated that the decoder complexity is manageable for AV1 with an averaged decoding run time relative to that of the HM decoder of about 66% for AV1.

As can be seen from Table 3, for the tested codec versions in [10], AV1 has a higher complexity compared to EVC and VTM4. Interestingly these figures are higher for the HD than the UHD resolution.

Table 3. Computational Complexity comparison between HEVC, AV1 and VVC [10].

Resolution Group/Codecs	HM	AV1	VTM
Resolution Group A (UHD)	1	9.37×	7.04×
Resolution Group B (HD)	1	14.29×	8.84×

As can be seen from Table 3, for the tested codec versions, AV1 has a higher complexity compared to EVC and VTM4. Interestingly these figures are higher for the HD than the UHD resolution.

In 2020 Fautier [12], compared the computational complexity of various codecs and the results are shown in Figure 4. AV1 has approximately 10 times the complexity of HEVC and this can be significant for ultra high-definition scenarios.

TABLE 3. Codec encoding complexity.

Codec	Reference	Note
AVC	Harmonic PURE	Commercial product
HEVC	Harmonic PURE	50% better compression than AVC
AV1	AOM version (May 2019)	Assuming on par or even better than HEVC
VVC	JM version (May 2019)	Target of reaching 50% better compression than HEVC

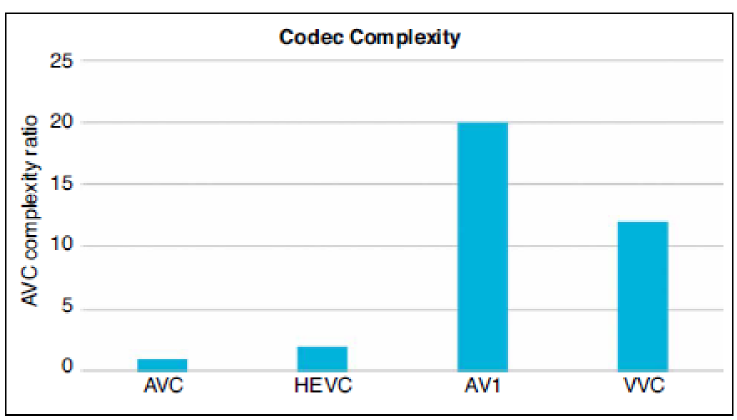

Figure 4. Experimental Results for compression efficiency for different encoders [12].

4. Conclusion

In conclusion, both AV1 and HEVC are excellent video codecs that offer high-quality video delivery. HEVC and AV1 are both advanced video codecs that offer high compression efficiency and improved video quality compared to older codecs. However, AV1 offers better compression efficiency than HEVC, thanks to the use of advanced techniques such as bi-directional prediction and Daala-based entropy coding. AV1 also uses smaller block sizes, which reduces the blocking artifacts that can occur in HEVC.

HEVC also has a more extended history and has been optimized for various platforms, which gives it an advantage in terms of hardware support for playback performance. While AV1 offers better compression efficiency and is free to use, HEVC remains the dominant codec in the market due to its widespread adoption and support. AV1 has a higher computational complexity which has been an issue with adoption on real-time platforms. However, with the increasing popularity of AV1 and its support from major companies and organizations, it may become a viable alternative to HEVC in the future with continuous improvements. As the video streaming industry continues to evolve, the choice between AV1 and HEVC will depend on the specific needs and requirements of each organization.

Overall, both codecs have their advantages and disadvantages, and the choice between the two depends on the specific use case and requirements. However, it should be noted that all the studies showed that VVC offers better compression efficiency and is a promising alternative for future video content delivery.

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